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Low-carbon innovation in non-domestic buildings: The importance of supply chain integration

Sofia L. Kesidou, Steve Sorrell*

Centre on Innovation and Energy Demand, Science Policy Research Unit (SPRU), University of Sussex Falmer, Brighton, BN1 9SL, United Kingdom

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ABSTRACT

Construction must play a major role in meeting climate change targets, but this will require major changes in industry practice. The sector will need to adopt innovative low-carbon technologies, integrate these within novel building designs and ensure these designs are constructed, implemented and optimised successfully. A likely precondition for this is greater levels of integration within the construction supply chain. While there is evidence that supply chain integration (SCI) can improve project performance and enable innovation, the literature rarely differentiates between different types of innovation and has paid little attention to low-carbon innovation. This paper synthesises insights from three different bodies of literature – construction innovation, low carbon buildings and SCI – to create a typology of low-carbon innovations in non-domestic buildings and to identify conditions and strategies for their successful implementation. It proposes that low-carbon innovations are 'building-enhancing' 'integral' and/or 'user-dependent' and their effective implementation requires collaboration, championing and user-involvement. The paper uses two case studies to illustrate the diversity of mechanisms through which these conditions can be realised. It concludes with some reflections on the methodological challenges of studying this topic, together with the wider implications of the proposed framework for industrial practice and public policy.

1. Introduction

The UK has a target to reduce national greenhouse gas emissions (GHG) by 80% below 1990 levels by 2050. Progress towards this target is stalling, with most of the reductions to date being achieved in the electricity sector [1]. To put the UK on course to meet this target, there needs to be acceleration in the rate of decarbonisation of buildings, transport, industry and agriculture. In the buildings sector, this is likely to require all new buildings to be 'near zero-energy' [2], in line with the requirements of the EU Energy Performance in Buildings Directive [3]. This will necessitate a step change in the way buildings are designed, built and operated [4].

New buildings offer the opportunity for radical reductions in carbon emissions through the large scale take-up of low-carbon innovations [5,6]. For non-domestic buildings, the transition can be encouraged from the top-down through policies such as building regulations and minimum efficiency standards, and from the bottom-up by engaging and educating organisations and users on the benefits of innovative, low-carbon solutions. Each approach comes with its own challenges and limitations [7]. For example, building codes provide no incentive to exceed the set targets and can be difficult to enforce, while entrepreneurs can find it difficult to obtain finance for new innovations. Between these two levels, there is a third, important, but often overlooked, 'middle' level of actors that frequently have the freedom (agency) and the ability (capacity) to act and deliver the change needed [8]. Professionals and practitioners within building supply chains are responsible for designing, planning, constructing and operating buildings and play a crucial role in initiating, delivering and promoting innovation [8].

Freeman [9] defines innovation as '*Any improvement in a process, product, or system that is novel to the institution developing the change*'. Within this wider context, innovations in the Architecture, Engineering and Construction (AEC) sector are defined as products (materials and components), processes and systems associated with the design and construction of built facilities [10]. Since building construction is both a manufacturing and a services industry, innovation exists on three levels, namely: the industry, the firm and the project [11,12]. For example, technological innovations that originate in manufacturing (industry level), are brought into construction through architectural, engineering and construction firms (firm level), and are realised within individual projects (project level) [13]. Due to this diversity, together with the highly customised nature of the built product, innovation in construction is complex and needs to be negotiated and coordinated

* Corresponding author.
E-mail address: s.r.sorrell@sussex.ac.uk (S. Sorrell).

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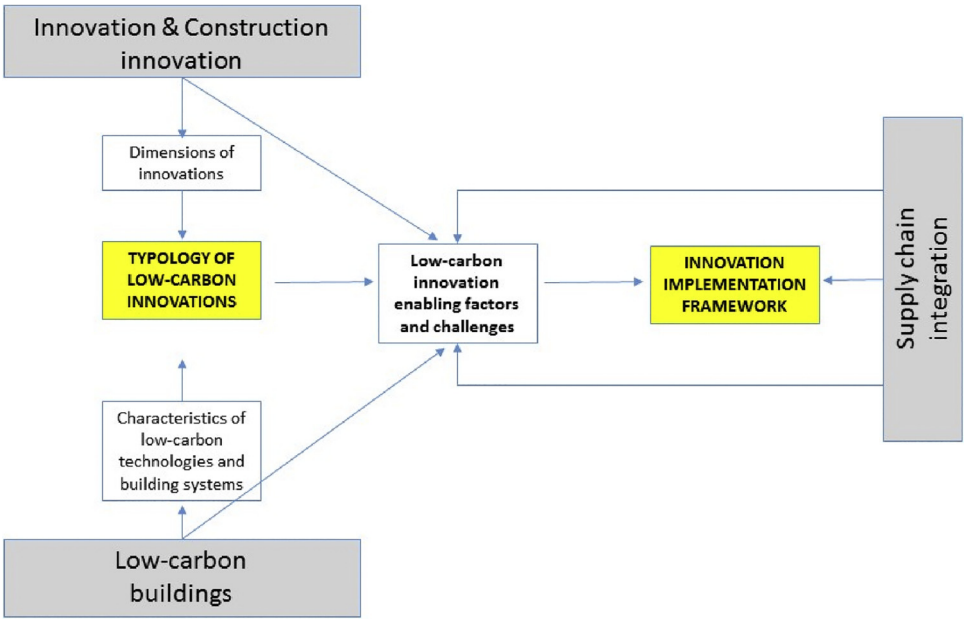
Innovation & Construction innovation
Dimensions of innovations
TYPOLOGY OF LOW-CARBON INNOVATIONS
Low-carbon innovation enabling factors and challenges
INNOVATION IMPLEMENTATION FRAMEWORK
Supply chain integration
Characteristics of low-carbon technologies and building systems
Low-carbon buildings

Fig. 1. Methodological approach to the literature review.

between different actors within project supply chains [14]. This clashes with the inherent structure of the sector, which has long been criticised for slow rates of innovation [15,16]. Building supply chains include a diverse range of actors - such as clients, users, investors, designers, contractors, sub-contractors, suppliers and manufacturers - that are usually involved sequentially in the project process. This fragmentation leads to variability in project performance, reduces productivity, inhibits learning and encourages adversarial relations. It also creates a barrier to innovation by inhibiting collaboration, coordination and knowledge exchange between the relevant actors [17].

As a result, one widely advocated measure to accelerate innovation is supply chain integration (SCI), defined as '*the merging of different disciplines and organisations with different goals, needs and cultures into a cohesive and mutually supporting unit*' [18]. The basic principle of integration is that a supply chain that delivers a product should not comprise disconnected functions [19]. However, integration is a multi-dimensional concept with many different constructs and definitions [20]. Studies of low-carbon and sustainable buildings tend to focus primarily upon integration in the design process. For example, Integrated Design (ID) relates to the integration of disciplines, information and building systems towards delivering the client's brief and improving building performance [21]. On the other hand, studies of construction management focus upon a broader concept of integration, involving relationships and governance arrangements that go beyond the downstream supply chain (client – design team – contractor) to include upstream actors such as sub-contractors, suppliers and manufacturers. However, this literature overwhelmingly focuses on improving traditional measures of construction productivity, such as capital cost and build times, rather than the performance of the building itself. And where the relationship between integration and innovation is explored, innovation is typically conceptualised as a single construct, thereby bypassing the intricacies of delivering different types of innovations in projects [22,23].

Fuelled by this disparity in approaches, this paper synthesises insights from a range of sources on how SCI can facilitate low-carbon innovations. The paper proposes a wider conceptualisation of SCI that has the potential to achieve traditional productivity goals, while at the same time optimising the energy and emission performance of buildings. The analysis focuses on non-domestic buildings, as this sector poses a greater challenge for integration owing to the complexity of the built product and the high level of fragmentation within the supply chain. The paper aims to answer the following questions:

(1) How and in what way do low-carbon innovations differ from other types of innovations in construction?
(2) What factors enable the successful implementation of low-carbon innovations in non-domestic buildings?
(3) How and in what way can SCI contribute to this successful implementation?
(4) What implications follow for academic research, industry practice and public policy?

The paper also discusses some of the methodological challenges faced during the project, and includes initial insights from two case studies.

The structure of the paper is as follows. The following section summarises the methodological approach to the review, while Section 3 classifies construction innovations along six dimensions. Section 4 maps low-carbon innovations against these dimensions and identifies their distinctive characteristics. A conceptual framework is proposed that distinguishes eight domains of innovation, each with their own challenges and enabling factors. This leads to the claim that a large number of low-carbon innovations tend to fall within three of these domains, being simultaneously 'building-enhancing', 'integral' and/or 'user-dependent'. Section 5 explores the factors that enable the implementation of these type of innovations in low-carbon buildings, while Section 6 discusses the SCI strategies that can allow this to occur. Section 7 uses two case studies to illustrate this framework, while Section 8 discusses the implications for research, industry and policy.

2. Approach and methodology

This paper is based on a comprehensive review of three bodies of literature - namely construction innovation, low-carbon buildings, and supply chain integration. The results are used to create a typology of low-carbon innovations, identify factors that enable and obstruct the implementation of these innovations, and show how particular supply chain integration strategies can facilitate their successful implementation. The main contribution of the paper is conceptual - developing a unifying framework that combines insights from these disparate bodies of literature. But the ideas are also tested using input from an industry expert and two case studies of recently completed low-carbon buildings.

Table 1
Terms used in bibliographic database searches.

Search term	Innovation in	Low-carbon buildings	SCI	Number of resources (Total)	Citation range/Year of publication range within first100 resources.
"Innovation" AND "construction"	■			1,813	60-629/1993-2015
"Innovation" AND "construction industry"	■			459	371-31/1992-2015
"Innovation" AND "low-carbon" AND "Building"	■	■		146	122-0/2007-2016
"Innovation" AND "low-energy" AND "construction"	■	■		18	52-0/2006-2015
"Low-carbon AND "technolog* AND "building"		■		208	109-6/2006-2016
"Systemic innovation" AND "building"	■			4	108-4/1998 - 2016
"Systemic innovation" AND "construction"	■			4	108-4/1998 - 2016
"Supply chain integration" AND "construction"			■	21	101-0/2003-2016
"Supply chain" AND "integration" AND "construction"	■		■	73	156-0/2001-2016
"Supply chain integration" AND "innovation" AND "construction"	■		■	7	101-0/2003-2014
"Partnering" AND "construction"	■	■	■	272	340-19/1990-2014

The grey shaded areas represent the three bodies of literature reviewed in the paper.

Fig. 1 outlines the approach to the literature review. This began by identifying key articles through bibliographic searches on the online Scopus database, using the search terms listedin Table 1. The results were initially filtered by year of publication (*1990 – 2016*), subject area (*construction, energy)*, keywords and publication type (*journal, articles*). The results were then sorted by number of citations and the top hundred publications were considered for abstract review. The publications selected for full review were those that provided useful insight into: (a) the different dimensions of construction innovation; (b) the characteristics of low carbon innovations; (c) the barriers and enablers to those innovations; and/or (d) the characteristics and strategies associated with supply chain integration. The evidence base was extended by following up the reference lists of the most useful papers. Literature on in-use building performance and the so-called 'energy performance gap' was identified through additional search strings in Scopus. Given the volume of literature in each area, the review was necessarily selective rather than fully systematic. Key literature was selected based on citations and relevance to the non-domestic sector. But recommendations on how the framework can be tested and extended are provided in the concluding section.

3. Classifying innovations in AEC

The literature on innovation identified in the review includes a plethora of classification schemes and typologies that largely exist in isolation from each other [24]. The same applies to the literature on construction innovation. Synthesizing insights from both, Table 2 distinguishes six dimensions of construction innovation, namely: type, origin, novelty, linkages, expected outcomes and actual outcomes. *Type* relates to the nature of the innovation or change; *origin* refers to the source of the innovation;

Table 2
Six dimensions of (construction) innovation.

Innovation dimension	Classification terms used in the literature	Indicative sources
Type	Product versus process; Technological versus organisational; Technical versus managerial.	[14,25–30]
Origin	Within firm, between firms, within projects; Multiple firms, open innovation; User-led versus supplier-led	[13,22,31,32]
Novelty	Incremental versus radical	[10,24,33]
Linkages	Modular versus systemic Integral	[10,13,33–38]
Expected outcomes	Product enhancing versus project process enhancing; Outcome-driven versus process-driven.	[10,17,31,39]
Actual outcomes	Disrupting, discontinuous, user-dependent	[40–43]

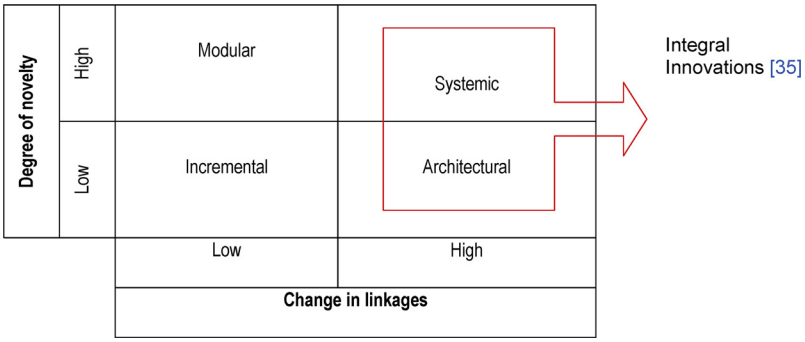

Fig. 2. A typology of construction innovations.
Source: Adapted from Slaughter [33].

linkages refer to the inter-connectedness of the innovation with other processes or systems; *expected outcomes* refers to the drivers of innovation; and *actual outcomes* refers to the achieved results of the innovation. Different studies focus upon one or more of these dimensions, but use a range of classification terms to subdivide each (Table 2, column 2). The following paragraphs elaborate further on each dimension.

3.1. Type

Innovation in construction can be technological, in the form of a new product or process, or organisational. Gann [14] examines technological innovation and explains that, although product and material innovations in construction are manufactured prior to on-site installation, there is still a high degree of innovation within construction supply chains. This happens through the modification and adaptation of technologies via feedback loops between producers, clients, designers and users [14]. Due to the inter-organisational nature of the industry, organisational innovation is frequently a pre-requisite for, or necessarily associated with, technological innovation [11,13]. Alternative procurement strategies and new managerial procedures are organisational innovations that facilitate greater levels of coordination within projects, thus enabling technological innovations. Gann [14] builds upon this observation to argue for the importance of project organisation in facilitating innovations.

3.2. Origin

Innovation is also categorised by its source, or origin. Davidson [13] differentiates between innovations that are sourced within the firm, from other firms within the construction industry or from firms outside the industry. The literature suggests that the construction industry is shifting from single firms being the originator of innovations to more 'open innovation' processes, where different firms initiate and coordinate efforts and exchange knowledge, resources and capabilities with external partners [44]. Innovations are also classified according to whether they are led by users or suppliers [45], or are project-based [36].

3.3. Novelty and linkages

These two dimensions are conceptually distinct, but closely linked. Under the *novelty* dimension, innovations are categorised according to the degree of change they embody compared to conventional products or systems. Under the *linkages* dimension, innovations are categorised according to number of linkages they have with other components or systems - and hence the impact they have on those components and systems. Slaughter [33] combines these two dimensions to give a fourfold classification, summarised in Fig. 2. *Incremental* innovations embody relatively moderate changes and have few links with other components or systems *Modular* innovations embody significant changes, but also have few links with other components or systems. *Architectural* innovations embody relatively moderate changes but have significant linkages with other systems. Finally, *systemic* innovations embody significant changes and have significant linkages with other systems.[1] Following Sheffer [35], we adopt the term *integral* innovations to group together systemic and architectural innovations, irrespective of the degree of novelty they embody (Fig. 2).

3.4. Expected outcomes

Innovations may also be classified by their expected outcomes, or the drivers behind their adoption. Two perspectives are relevant here. From the perspective of an innovating firm, the introduction of a new or improved product or service can allow the firm to gain competitive advantage, realise value, expand existing markets, develop new markets and/or adapt to new regulatory standards [17]. From the perspective of individual projects, innovations may improve the project process (process-driven), improve the building product (outcome-driven) or a combination of the two.

3.5. Actual outcomes

This dimension relates to the actual and tangible effects derived from the implementation of an innovation, which may either align or diverge from the expected outcomes. For example, Robertson [46] uses the term 'discontinuous' to refer to an innovation that requires users to change their patterns of behaviour, and the term 'disruptive' to refer to an innovation that results in a greater market share than that of existing, competing products. In the case of buildings, innovation is highly dependent on user behaviours and patterns of use and these may facilitate or obstruct the realisation of expected outcomes. This makes the impact of user-dependent innovations very difficult to predict.

The following section uses these six dimensions to establish what is distinctive about low-carbon innovations.

4. Conceptualising low-carbon innovations in new building construction

4.1. The distinctive character of low-carbon innovations

In considering how low-carbon innovations map onto the six dimensions, the literature highlights the following characteristics as being particularly relevant:

[1] Slaughter also defines *radical* innovations, that: a) introduce entirely new concepts or approaches; b) have major implications for links with other components or systems; and c) have the potential to make existing products and processes obsolete [10]. Radical innovations are excluded from this review, however, as their high risk makes them an infrequent occurrence in construction [19,35].

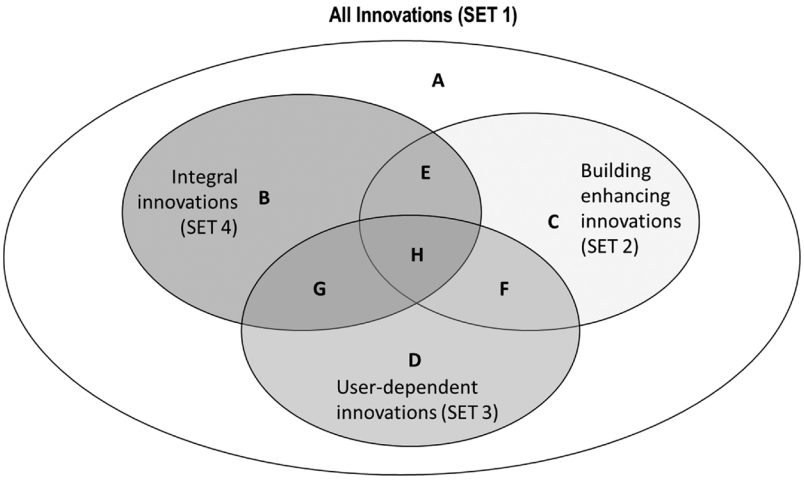

Fig. 3. Different types of construction innovation.
Source: Authors.

- Energy systems for non-domestic buildings are complex and their performance depends upon exploiting synergies between different building components and sub-systems. [47].
- The performance of energy systems depends upon the behaviour of users, and can therefore diverge substantially from that anticipated [48];
- Technologies, materials and components are widely available to produce low-carbon buildings, but their successful implementation requires significant changes in design, management and construction practices [29].

Based on the above considerations, low-carbon innovations do not appear distinctive in terms of their type and origin, since they vary as much on these dimensions as do other types of innovations. The same applies to novelty, as the risk-averse nature of the industry generally discourages radical innovations. However, low-carbon innovations tend to have distinctive properties under the other three dimensions, namely:

- *Linkages*: they tend to be integral (architectural or systemic) in terms of their extensive impacts on other systems and components during delivery;
- *Expected outcomes*: they are primarily driven by the need to enhance the building product, rather than the project process; and
- *Actual outcomes*: their effects and performance rely, to a great extent, on user-behaviours.

In Fig. 3, *Set 1* includes all types of construction innovation. Within this, we define three sub-sets*: Set 2* contains all *integral* innovations*, Set 3,* contains all *building-enhancing* innovations and *Set 4* contains all *user-dependent* innovations. These three subsets, and their intersections, create eight distinct domains. The claim here is that in low-carbon buildings, a large number of innovations fall within three of these domains – namely *E, F* and *H*. In other words, to achieve the level of carbon reductions needed in such buildings a combination of innovations that are building-enhancing, as well as integral *(E)*, user-dependent *(F)* or both *(H)* need to be specified. To successfully deliver high-performance low-carbon buildings, while at the same time minimising capital costs and ensuring project process efficiencies, there is a need to go beyond modular innovations, where single disciplines and trades deliver services and components with minimal interactions and where little attention is paid to in-use optimisation. Instead, there is a need to employ innovations which have significant impacts on other building systems and which depend upon the behaviour of users. This combination of characteristics sets low-carbon innovations apart from many other construction innovations.

The following section provides some support for this claim by examining the characteristics of 40 representative low-carbon innovations, together with the adoption of those innovations within two case study projects.

4.2. Illustrative mapping of low-carbon innovations

To assess the above propositions, a representative list of 40 low-carbon technologies in building construction was put together and each technology was allocated to one of the eight domains of Fig. 3. The mapping of the different technologies was achieved through triangulation of three sources, namely: a) input from an industry expert with a background in building physics and environmental building design; b) a review of the technical and academic literature on the different technologies; and c) the judgement of the first author based on her previous experience in building environmental assessments and sustainability consultancy. The industry expert was asked to assign scores to each technology as follows:

- *Novelty*: allocate a score from 0 to 5 to represent the extent of departure from a standard, or base case technology (high scoring technologies are classified as novel);
- *Linkages*: allocate points for the number of different actors involved in the implementation of the technology compared to a base case technology (high scoring technologies are classified as integral);
- *Actual effects:* allocate a score from 0 to 5 to represent the extent to which the technology requires users to change their behaviour (high scoring technologies are classified as user-dependent).

The first two scores allow the innovation to be classified as either incremental, modular, architectural or systemic, while the last score allows the degree of user dependence to be assessed. The scores assigned by the industry expert were checked against a review of relevant literature and the judgement of the first author, with minor adjustments been made in some cases. Once the scoring was complete, each of the technologies was assigned to one of the domains in Fig. 3.

The inputs and results of this exercise are presented in Appendix A, which maps the 40 technologies onto the 8 domains identified in Fig. 3. Figs. 4 and 5 summarise the findings. All of the 40 technologies evaluated are classified as building-enhancing, with 17 being classified as integral, 16 as user-dependent and 28 (70%) as situated in domains E, F or H of Fig. 3. So more than two thirds of the technologies in this sample have the distinctive characteristics identified in the previous section.

The classification of individual low-carbon innovations under the eight domains is subjective, given that the boundaries of each set are

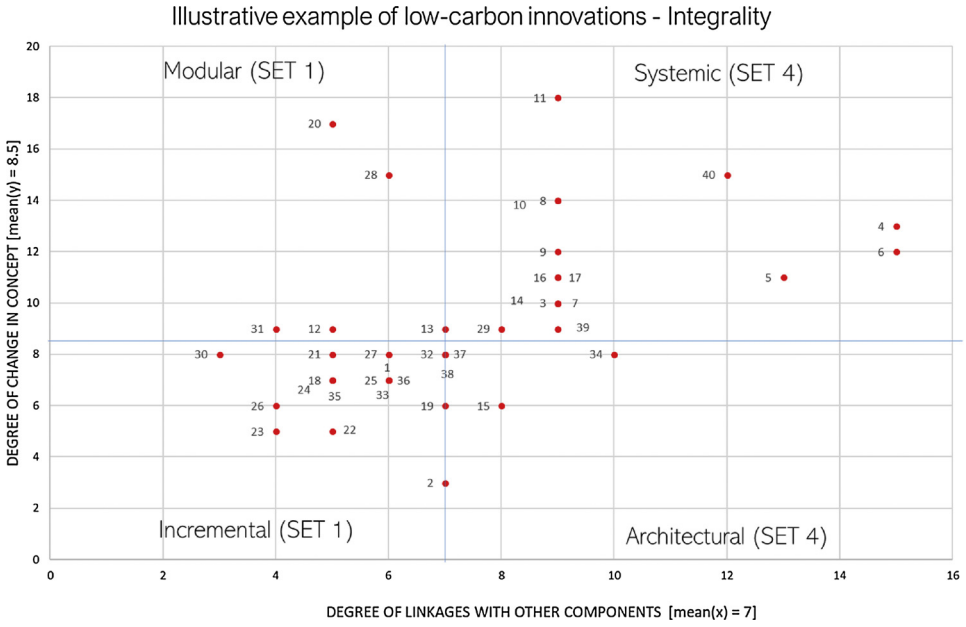
Illustrative example of low-carbon innovations - Integrality
Modular (SET 1)
Systemic (SET 4)
Incremental (SET 1)
Architectural (SET 4)
DEGREE OF CHANGE IN CONCEPT [mean(y) = 8.5]
DEGREE OF LINKAGES WITH OTHER COMPONENTS [mean(x) = 7]

Fig. 4. Classification of selected low-carbon innovations in terms of 'integrality'.
Note: Numbers refer to the innovations listed in Annex A.

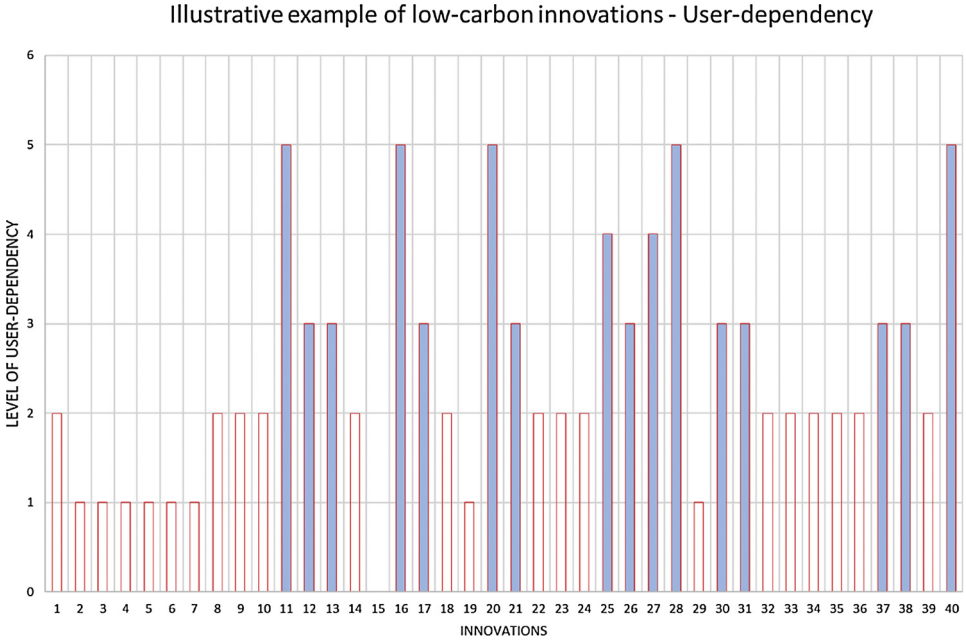

Fig. 5. Classification of low-carbon innovations in terms of user-dependency.

fuzzy and sensitive to context. Moreover, a range of technologies and processes are employed in low-carbon buildings, making it difficult to formulate an implementation strategy that is suitable for each. However, the framework can be used to map the 'innovation footprint' of a particular building and thereby provide an orientation for the implementation strategy.

4.3. Low-carbon innovations in two case study building projects

To illustrate this framework further, we summarise the initial results of two case studies (A and B) of recently completed low-carbon buildings in the UK.

Building A is a high-performing business centre that has won numerous sustainability awards. The occupier is a wholly owned subsidiary of the client organisation with strong credentials in the area of sustainability. The scheme is innovative in terms of building performance (BREEAM[2] Outstanding, low embodied carbon, EPC A and DEC A[3]), technologies employed and processes used for project delivery. The building includes a number of innovations to achieve PassiveHaus

[2] BREEAM is an international scheme that provides independent third-party certification of the assessment of a building's environmental, social and economic sustainability performance. The outcome is a rating from 0 to 100%, where > 85% is 'Outstanding'.

[3] Under the recast EU Directive on Energy Performance in Buildings, the energy efficiency of buildings should be made transparent through Energy Performance Certificates (EPCs) that are issued for each property when it is built, rented or sold. Public buildings, under the same directive should report and display their energy performance through Display Energy Certificates (DECs).

Table 3
Low carbon innovations employed in the two case studies.

Case	Low-carbon innovations:	Domain
Case Study A	Passivehaus	H
	Pre-fabricated wall cladding system with high levels of insulation	E
	Roof-mounted PV	F
	Demand-led ventilation with carbon dioxide sensors/ openable windows	F
	Combined Heat and Power (CHP)	E
	Integrated shading	C
	Localised lighting with controls built into BMS	F
Case Study B	Photovoltaics (with energy storage)	F
	Waste heat recovery and waste CO_2 recovery	E
	Water source heat pumps	E
	Rainwater gardens/Green roof	H
	Hybrid mixed mode ventilation	F
	Building Management System (BMS)	F
	High performance glazing	C
	Localised lighting with controls built into BMS	F

Note: Classification of technologies in line with Annex A.

standards, together with a prefabricated wall cladding system. These can be described as *integral* since they require a collaborative design and construction process that affects all disciplines, as well as being novel for the client and for much of the UK industry. They are clearly *building-enhancing* and the high level of customisation creates additional risks for project delivery. They are also *user-dependent* since the PassiveHaus features require fine-tuning with operational requirements and occupancy patterns. Hence, they fit the pattern identified above.

Building B is an educational facility with a strong focus on innovation, sustainability and environmental performance. The building includes many innovative technologies, such as renewable energy generation with energy storage, water-source heat pumps and heat recovery. The building is intended to provide a real-life laboratory for monitoring and understanding energy-efficient building design. This requirement was incorporated in the project brief and formed the philosophy behind the project organisation. The delivery of the various innovations required a high level of collaboration and integration within the project team, as well as the extensive involvement of users. Although complex, the building was delivered on time and to budget, and is performing to specification within its first few months of occupation.

Table 3 summarises and classifies the key low-carbon innovations employed in each building – all but two of which fall in domains E, F or H of Fig. 3. Hence, these two illustrative case studies support the argument of the previous section.

5. Implementation Framework for low-carbon innovations in non-domestic buildings

So far, this study has identified the distinctive characteristics of low-carbon innovations in non-domestic buildings, drawing from classification schemes found in the construction innovation literature. This section expands on this, to identify factors that enable or obstruct the implementation of each type of innovation. The characteristics of innovations in domains E, F, and H imply the need for wider and more effective cooperation between different disciplines and organisations throughout the construction process - or in other words, they imply the need for greater levels of SCI. Following Slaughter [10,33], it is argued that each type of innovation is facilitated by a particular implementation strategy. Sections 5.1–5.3 present the enabling factors for building-enhancing, integral, and user-dependent innovations respectively, while Section 5.4 presents the SCI implementation framework that results.

5.1. Low-carbon innovations as building-enhancing innovations: the importance of championing

Low-carbon building innovations may be defined as new technologies, processes and products that affect a building's operational energy use and carbon emissions. At a project level, construction innovation aims to improve the project process, through reducing costs and construction times, and/or improve the building product through improving quality and performance [49,50]. Low-carbon innovations belong to the latter category, since their primary objective is enhanced building performance. The drivers may be client demand for lower energy costs and improved sustainability, or public policies at the national or local level (e.g. building regulations, planning regulations).

Low-carbon innovations mostly originate within engineering design disciplines and sub-contractor trades [51] and their beneficial impact on energy costs and emissions may or may not be accompanied by improvements in construction project performance. For this reason, it may be more difficult to include such innovations within building projects, as most stakeholders have only weak incentives to make buildings perform better after completion [52]. While clients may have an incentive to minimise whole-life costs, contractors and consultants are rarely accountable[4] for the operational performance of a building and hence may seek to maximise profits at the expense of building performance [6]. It is for this reason that implementation of these innovations typically requires **championing** by an actor within the project supply chain. Championing is associated with strong agency, dedication and drive focused around specific innovations or outcomes [53]. These champions must also have the power, resources and capacity to act, since a mismatch between agency and capacity creates barriers to change [8].

5.2. Low-carbon innovations as integral construction innovations: the importance of collaboration

Low-carbon buildings must minimise reliance on electricity and fossil fuels for services such as lighting, heating and cooling, whilst achieving high standards of service quality. Underpinning the delivery of such buildings is the principle of system-level or whole-building performance [54]. The largest energy-saving opportunities arise through considering the building as a system and optimising how the different elements work together, rather than relying on specific energy-efficient and low-carbon technologies in isolation [47]. Strategies to achieve low-carbon goals are therefore based on synergies between different parts of a building system and depend upon both architectural design and user behaviours. Coordination and co-operation between different disciplines and trades is essential during both design and construction, together with the involvement of users. Innovation in low-carbon buildings should therefore be examined not only in terms of the magnitude of change and improvement they embody compared to existing technologies, but also the degree to which the new technologies operate autonomously or affect other building components and systems [55].

Since energy-saving opportunities at the system level are substantially greater than at component level, integral innovations (i.e. both systemic and architectural) are key to improving energy and emission performance [34]. These necessitate multiple firms to collaborate or change their practice in a coordinated way which in turn requires careful management, tacit knowledge, regular informal communication and organisational learning [36,56]. For example, Mlecnik

[4] Alterative contracting arrangements for example through Energy Performance Contracts (EPCs) are available in construction, but rarely delivered by general contracting firms. In the case of non-domestic buildings, there are also complexities relating to leasing, selling and changes in use of the properties that create uncertainties given the long-term nature of EPC contracts.

[57] explores the processes involved in the implementation of systemic innovations in the construction of low-energy housing and stresses the importance of collaboration between suppliers and other organisations. Unlike incremental and modular innovations that can be introduced at any point in the design and construction process, systemic innovations need to be introduced at the early design stage by technically competent actors that have a coordinating role without a vested interest in retaining existing configurations. Mlecnik finds that technological innovations of any type have the potential to become systemic when collaboration and interaction within wider networks is facilitated. Similarly, architectural innovations have stronger potential for successful implementation when they originate from disciplines with knowledge and control over the linkages between the various elements and modules and when they are recognized and planned for early in the project [10]. Examples of systemic innovations in construction include Building Information Modelling (BIM), modularisation and prefabrication of building components, lean construction processes and 3D CAD design and construction tools [33,38]. To successfully implement these types of innovation, **collaboration** between different disciplines and trades is essential. This points to the need for greater integration, both internally within the construction industry and between the construction industry and external parties, such as the property and manufacturing sectors.

5.3. Low-carbon innovations as user-dependent innovations: the importance of user involvement

For low-carbon innovations that are user-dependent, performance is sensitive to occupancy patterns and operational management procedures. The significance of this user-dependency is highlighted in the literature on low-carbon buildings, which identifies user-involvement as critical for reducing emissions [58]. User-dependency creates uncertainty in the performance of these innovations which in turn can hinder their adoption. Unlike, for example, a new wall insulation product that is fitted on a building during construction and whose performance remains unchanged during the building's lifetime, the effectiveness of a mixed-mode ventilation system depends upon optimisation and building management procedures during occupation. This uncertainty can be mitigated by **involving users** in the project process in three ways. First, users (including facilities managers and building occupants) should be able to influence the design from an early stage, so that low-carbon innovations align with their anticipated needs and behaviours [58]. Second, users should participate in building system optimisation throughout the design, construction, commissioning and operational stages, so they can influence and fine-tune performance considering their needs and expected use patterns [59]. Third, post-occupancy evaluations (POEs) should be conducted and their findings utilised to increase industry awareness of the operational performance of different building types and technological configurations, as well as the contribution of users to that performance [60]. For speculative buildings, where the users are not known, engagement with user bodies (e.g. British Council for Offices), the use of green leases and the establishment of operational standards for landlord services[5] could contribute to reducing the performance gap.

5.4. Implementation framework for low-carbon innovations in non-domestic buildings

Fig. 6 summarises the proposed conditions for successful implementation of low-carbon innovations that follow from the above analysis. The figure identifies a key enabling factor for implementing each type of innovation and demonstrates that a *combination* of enabling factors is required to successfully implement innovations that share two or more of these characteristics. This highlights the need for greater levels of supply chain integration, explored further in the following section.

6. Supply chain integration and low carbon innovation

6.1. Perspectives on supply chain integration and construction innovation

The literature review identified the characteristics of low-carbon innovations, the enabling factors for their implementation and the prevailing conditions in the industry that hinder their implementation. Most of these obstacles arise from the fiercely competitive and fragmented structure of the industry and can be summed up as follows [6,61]:

(1) The separation of design, construction and operational phases, whereby different disciplines participate and input sequentially. This contributes to a lack of 'systemic vision' within projects and hinders integrated design and collaboration during the key early stages.
(2) The continuously changing coalitions of supply chain actors in different building projects, leading to lack of trust and misalignment of objectives. Due to the temporary nature of projects, feedback loops between clients, supply chain actors and users are often weak or non-existent.
(3) The proliferation of general contracting and sub-contracting of the various building trades, resulting in the lack of a coordinating and integrating focal presence in projects that could promote innovation and act as a bridge between demand and supply. This also leads to an industry geared towards optimising the project process rather than the performance of the completed building.

This set-up has been heavily criticized for its potential to create conflict and adversarial relations at all stages of the building process and for its negative impact on the quality of the finished product [16,62]. A fragmented industry also inhibits the delivery of low-carbon buildings and the diffusion of low-carbon innovations. Specifically, it hinders the exploration and exploitation of the complex interactions and synergies that need to be addressed early on to achieve energy performance and indoor comfort goals; it prioritises process efficiencies rather than the performance of the building product; and it obstructs the formation of feedback loops between supply chain actors, clients and users. In principle, supply chain integration should alleviate these effects, allowing low-carbon innovations to be encouraged and the energy performance of buildings to be improved.

Supply chain integration aims to reduce the negative effects of fragmentation and improve effectiveness and efficiency in delivering the building product [63]. *Collaborative relationships* are the primary objective, defined as a process of sharing skills, expertise, understanding and knowledge under an environment of trust, openness and mutual respect, with the aim of delivering optimum solutions and meeting common goals [21,64]. Table 4 identifies the key strategies contributing to an integrated supply chain identified in the literature review.

SCI studies tend to focus primarily on improvements to the construction process and traditional measures of project performance [60]. There are few studies that explore the relationship between integration and innovation, and those that do either examine innovation as a singular concept or focus on innovations located in domains A and B of Fig. 3. For example, Ozorhon et al. [27] conduct case studies of two innovations - Modern Methods of Construction (MMC) and lean construction – that belong in domain B. They find that the use of partnering between the client and contractor (which was also extended to suppliers and consultants), together with the effective leadership of the client and

[5] In commercial speculative developments, landlords are responsible for providing core building services such as a central system for heating and cooling air or water, common areas lighting, power, lifts, external lighting etc. Tenants typically plug in their own systems and fit interior spaces according to their own specifications.

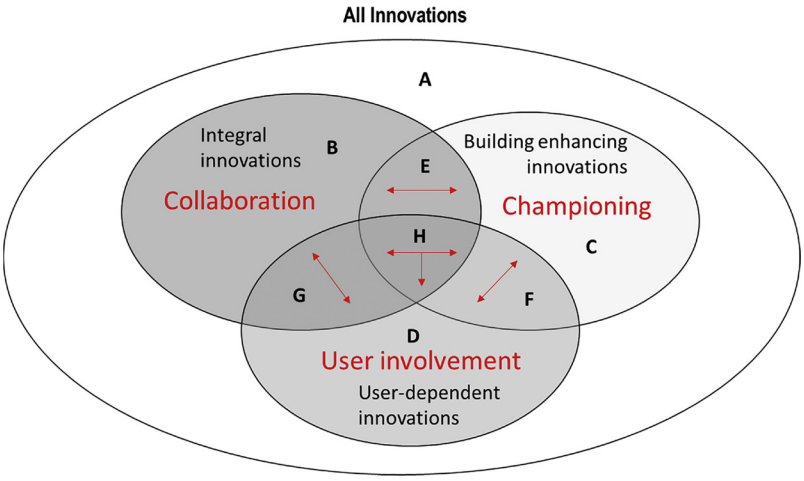

Fig. 6. Conditions for the successful implementation of low-carbon innovations in construction.

Table 4
Strategies contributing to an integrated supply chain.

Long term and high-involvement relationships between clients, contractors and sub-contractors	[65–67]
Continuity in the management of design and construction phases	[20,68]
Early involvement of sub-contractors and suppliers	[64,69]
Contractual arrangements that share risks and rewards amongst parties and align goals and objectives, thereby creating the conditions for establishing effective collaboration and a no-blame culture	[39,70]
Relational and informal contracts[a] in combination with some contractual safeguards	[67,71]
Establishment of collaborative tools and processes (such as Building Information Modelling (BIM), co-location of actors, regular workshops) at both project and firm levels	[20,72]
Use of digital communications and project management tools, Building Information Modelling (BIM) and online tendering systems	[69]
Systems and processes integration, enabling effective management of communication and information flows	[19,31]

[a] Relational contracts include various approaches, such as partnering, alliancing and joint venturing. They promote more cooperative relationships through the recognition of mutual benefits between the parties. Relational contracts are usually long-term, develop and change over time, and involve substantial relations between the parties.

contractor, acted as enablers for these innovations. Similarly, Ling et al. [73] explore top-down construction (domain B) in a case study of mixed-use development in Singapore and find that client involvement as the developer and project manager contributed to a win-win situation for the supply chain and was a key reason for the project's success. Holmen et al. [11] explore timber-frame multi-storey construction (domain B) in two Norwegian projects and find that tight relationships within the supply chain encourage learning across projects and foster innovation. However, such relationships reduce flexibility for individual firms so they tend to be undervalued in the industry. Finally, Mlecnik [57] explores the innovation journey of structural timber wall construction (domain B) for Passivehaus housing projects and notes the important role of suppliers and manufacturers in transferring knowledge for the development of systemic innovations.

The following three subsections identify SCI strategies relevant to the three enabling factors for implementation identified above - namely collaboration, championing and user-integration. The main lessons are summarised in Table 5.

6.2. Collaboration: the importance of long-term relationships and trust

Integration involves inter-organisational collaboration [74], and has been defined as "*the degree to which a focal company strategically collaborates with its supply chain partners and collaboratively manages intra and inter-organizational processes*" [74]. Collaboration signifies an interactive process involving joint decisions and activities. **Long-term relationships**, between different parties are key to achieving collaboration, and thereby innovation in construction [35,68]. However, the most common model is short-term, market-based exchanges within the confines of individual projects. The importance of long-term, trust-based relationships is highlighted by Baiden [18], Kumaraswamy et al. [67] and Lloyd-Walker [75], who argue that the collaborative environment formed by these relationships creates a no-blame culture that fosters learning and information sharing. Long-term relationships also promote **trust** which allows project actors to jointly share the risks and benefits of innovation. Long-term relationships further promote the alignment of objectives and encourage experimentation towards meeting common goals. But improving construction performance in this way is likely to require a fundamental change in the management of relationships between clients, contractors and sub-contractors [76].

Table 5
Strategies contributing to the successful implementation of low-carbon innovations in non-domestic buildings.

Type of Innovation	Implementation condition	Strategy
Integral	Collaboration	Long-term, trust-based relationships between actors Collaborative tools
Building-enhancing	Championing	Client involvement Innovation brokers Innovation champions System integrators
User-dependent	User-integration	Early involvement of users Post-occupancy evaluations Post completion after-care of buildings

For non-domestic buildings, the effectiveness of technological and operational systems can only be assessed through systematic post-occupancy evaluation (POE). Similarly, integral, user-dependent innovations require an optimisation process where designers, contractors and users fine-tune components for optimum performance. In traditional procurement, the role of designers and contractors ends upon building completion which greatly reduces the opportunities for evaluation, learning, knowledge-sharing and optimisation. Under traditional contracts, designers and contractors have little incentive to learn and to optimise the performance of the built product. Given the discontinuous nature of project-based construction, only suppliers and manufacturers are interested in learning between projects. This contrasts with the manufacturing sector, where firms operate in relatively stable markets and commonly maintain in-house R&D programs that include learning feedback loops

that facilitate innovation [77]. For these reasons, **long-term, trust-based relationships** between construction and other sectors, such as manufacturing, are likely to be instrumental for innovation.

6.3. Champions: the importance of client involvement, innovation brokers and system integrators

Many studies find clients to be influential in driving and championing construction innovation [27,78], due to their capacity to develop detailed project requirements and to exert pressure on other participants. Barlow [78] notes that clients need to be 'demanding' and 'experienced' to be able to stimulate innovation in their projects. The client's role in facilitating innovation is documented in several case studies, including those by Ling et al. [73] and Ozorhon et al. [27]. In both of these case studies, clients were demanding and knowledgeable and their participation in the projects ensured that innovative solutions were found that benefited all parties.

The importance of **client involvement** has several implications for low-carbon innovations. Where modular or incremental innovations are driven by the need to improve project process efficiency (domain A), client knowledge and involvement should be less important. These innovations are delivered within single disciplines, with benefits appropriately distributed to the innovating firm. As noted by Bordass et al. [40], new technologies which improve the speed, cost or quality of construction are of strong interest to the supply-side, but also of interest to clients since they facilitate the faster construction of better and cheaper buildings.

Client involvement becomes more important for integral innovations (domain B) and particularly for those that are building performance driven and/or user-dependent (domains E, G, and H). These innovations entail greater uncertainty and the benefits and risks are not evenly shared between participants in the innovation process. New technologies that improve building performance need more time, money and effort to orchestrate, nurture and optimise and thus carry risks. These reduce incentives for adoption across the supply chain [40]. The role of a knowledgeable and committed client in these cases is critical. Such a client can set the innovation agenda early on and ensures the use of procurement and contractual arrangements that align objectives and allocate risks fairly. An active client would be heavily involved during both design and construction, thus encouraging the exploration of new ideas and the exploitation of existing knowledge within the project [26].

Unlike most types of manufacturing, where volumes and frequencies of production are high and focal firms are knowledgeable and directly involved in production; in construction client types and roles vary significantly. For non-domestic buildings, for example, there is a range of client types, including owner occupiers, portfolio owners, speculative developers and managing agents. These have differing degrees of experience in construction procurement and operate with diverse profiles (e.g. private, public, commercial, domestic) and incentives. Since knowledgeable clients are rare [79] and since there are few examples of low-carbon buildings from which to learn, low-carbon innovations – and in particular those situated within domains E, G and H – tend to face greater obstacles than other types of innovation.

Hence, in addition to client involvement, there is a need for **innovation brokers** and **innovation champions** in projects. Innovation brokers can be professional institutions, trade associations and knowledge-exchange bodies that accelerate the uptake of innovations by acting as intermediaries [80]. Innovation champions are defined as individuals who "actively and enthusiastically promote innovations through the crucial organisational stages, and are necessary to overcome the social and political pressures imposed by an organisation and convert them to its advantage" [53]. However, the prevailing fragmentation of professional bodies within the industry hinders the effective brokering of innovation [31]. Alternative contract solutions based on the principle of integration for products and services have emerged in response to the need for long-term relationships within the supply chain. These provide clients with comprehensive support over the whole building lifecycle, including financing, design, systems integration, implementation, construction, technical support, commissioning, maintenance, operation and de-commissioning [14]. Integrated procurement routes, in turn, re-establish the importance of long-term relationships and facilitate the emergence of innovation champions.

The structure and organisation of projects can also contribute to innovation. The role of suppliers as initiators of innovation is widely acknowledged [12,57], but under traditional procurement routes sub-contractors and suppliers are brought in at a late stage and have little or no links to clients or users [68,81]. There can be benefits therefore, from involving suppliers and sub-contractors at an early stage within an integrated design process [57]. Similarly, there are benefits from managerial procedures that promote joint activities and collaborative working through tools such as joint IT systems, team-building activities, co-located project offices and regular workshops.

The literature also highlights the role of a systems integrator, which has been extensively explored in studies of Complex Products Systems (CoPS) [82]. Systems integrators have detailed knowledge of client requirements, the skills to integrate interdependent components and knowledge of industry rules and regulations [82]. Winch [31] argues that innovation in construction suffers because the system integrator role is shared between the architect/engineer and main contractor and there is typically a split between design and construction. The existence of a system integrator can enhance inter-organisational cooperation, but only when a single entity is contractually responsible for performance, not when the role is split. This has implications for low-carbon buildings, where complexity is high and integral innovations need to be negotiated between parties.

6.4. User-integration: the importance of early user involvement and post occupancy evaluation

There is often a significant gap between the predicted energy performance of a building and its operational energy performance - defined in the industry as the 'energy performance gap' [41]. A range of factors contribute to this gap, including lack of accurate information at the design stage on occupancy profiles and user behaviours, inconsistent information on material properties, underestimation of heating and cooling loads, lack of time for building commissioning and weak incentives to optimise building performance [40,83]. The possible 'unintended consequences' of low-carbon innovations and the need to shift the focus of the industry from production to 'in-use' performance was highlighted in a series of post-occupancy evaluation (POE) studies undertaken between 1995 and 2002 [84,48]. Since then, many studies and voluntary initiatives have emerged encouraging a shift of focus towards in-use performance [85,86]. For low-carbon buildings, such studies become even more important. Under typical practice, designers and contractors leave a project behind upon completion. With POEs and wider building performance evaluation methodologies[6], building owners and managing agents can optimise the performance of systems and design teams and contractors can acquire knowledge about that performance and use this in subsequent projects. But there is still a long way to go before POEs become the norm in the industry, and their results become systematically used [48].

The user perspective is rarely presented as a component of SCI [87], although occupants and facilities management are critical for delivering

[6] Building Performance Evaluation (BPE) is a wider process of evaluating the performance of a building with Post Occupancy Evaluation (POE) being one of its major parts. It can be carried out in new, existing and refurbished domestic and non-domestic buildings. (Source: https://www.bsria.co.uk/services/fm/building-performance-evaluation/).

better building performance and innovation. Procurement routes that enable continuity between design, construction and operation, together with contractual arrangements between clients and contractors that ensure sufficient 'aftercare' allow greater user involvement in project delivery. **User integration** is also facilitated by 'high-involvement' relationships between clients, designers, contractors and users, together with external bodies such as research institutions and non-profit organisations. These links facilitate effective knowledge and information flows.

In sum, the successful implementation of low-carbon innovations is no easy task and is likely to require a combination of strategies that are associated with, and facilitated by, supply chain integration. By implication, the presence of some but not all of these strategies is likely to be insufficient for the successful delivery of low-carbon buildings.

7. The framework in practice – insights from two case studies

This section illustrates the proposed framework using two case studies of recently completed, low-carbon non-domestic buildings (A and B). Data was collected through semi-structured interviews with the client and project team, together with reviews of secondary documentation. The findings suggest that collaboration, championing and user-involvement were key elements of both projects, with several aspects of SCI incorporated in project organisation and procurement. However, the mechanisms and structures used to create these conditions varied significantly between the two case studies. These are briefly summarised below.

7.1. Case study building project A

The project was competitively tendered and procured through a single-point delivery route, whereby the contractor is responsible for both design and construction. The knowledgeable and experienced client assumed a championing role within the project, from selection of the winning entry to delivery of the brief and post-completion aftercare. Whilst the project was contactor-led, the client attended workshops and meetings and negotiated with the contractor over specifications and procedures, so that expected outputs were evaluated against both economic and environmental criteria. The client observed that: "…*we wanted to make sure that all relevant outcomes were reported and addressed and stayed on into the project.*" An additional championing role was assumed by the project architect, who was part of a skilled firm specialising in PassiveHaus design.

Collaboration was central to the project from the outset. The selection of the winning bidder was based on criteria, such as cost, deliverability and aesthetics, but "….*if any of the teams indicated they could not collaborate, we would not appoint them. That was critical. They needed to demonstrate they were one integrated team*". Formal collaborative procedures were employed, such as Building Information Modelling (BIM) which uses digital interfaces to integrate information flows across disciplines and throughout a project's life-cycle. In addition, project horizon scanning was used to enable team members to report their difficulties and to identify potential risks.

Users were also integrated throughout the project process, contributing to the selection of the winning bidder and participating in regular workshops with the project team. Users were also involved after completion through protocols for building aftercare that ensured optimal performance.

7.2. Case study building project B

The project was procured under a Design and Build route, where the contractor has responsibility over design and construction. The client and the user groups were knowledgeable and experienced in sustainable design and construction and their involvement in all stages of the project was instrumental. This included developing the brief and tendering, where the ability of the applicants to strike a rapport with the user group was one of the criteria for selection. User-involvement continued through the design and construction stages with users attending regular meetings and providing input regarding the technologies and building features. Users were also involved in commissioning and fine-tuning the building to achieve optimum performance. Protocols for aftercare were in place and ongoing after handover.

The client's knowledge of sustainable building design, combined with the commitment of the contractor-led team to deliver the brief, helped create a highly collaborative environment. As the client suggested, *"That is the difference…, It was not just your standard project…They (the team) bought into the concept and they gave it the resource it needed to be a success… and it was a success.*" The project did not employ any novel collaborative tools or relational contracts. However, the client allowed the main contractor to select their own team, including the architect. In addition, the team employed a bespoke sustainability framework, developed by the client that went beyond standard BREEAM requirements. This facilitated creative collaboration to deliver high environmental standards and encouraged the team to "*think outside the box*".

The client team, including various user-groups, was highly involved into the project and sustainability was a priority throughout. The client's knowledge of sustainable building design allowed them to negotiate and defend several design options that, although more expensive, delivered better outcomes in terms of energy costs and environmental performance. This also ensured that clashes between different user aspirations were minimised and addressed at an early stage. User awareness and knowledge in operational aspects also contributed to a more effective commissioning and hand-over process.

8. Conclusions and implications

This paper has synthesized insights from three different bodies of literature - construction innovation, low-carbon buildings, and SCI - with the aim of creating a typology of low-carbon innovations, identifying enabling factors, developing a conceptual framework for their implementation and identifying supply chain integration strategies that can contribute to their implementation. The review began by identifying six dimensions of construction innovation, namely type, origins, novelty, linkages, expected outcomes and actual outcomes. This led to the identification of three distinguishing features of many low-carbon innovations, namely building-enhancing, integrality and/or user dependency (Fig. 3); together with three corresponding enabling factors for their implementation: championing, collaboration and user integration (Fig. 6). The review then discussed how many of the obstacles to low-carbon innovations can be overcome through greater supply chain integration, highlighting the importance of: long-term, trust-based relationships; collaborative tools; client involvement; innovation brokers; early involvement of users and post-occupancy evaluations (Table 5). Finally, two empirical cases studies were used to test the proposed framework.

The following sections provide some reflections on the methodology, suggest some directions for future research and highlight some of the implications for industry practice and public policy.

8.1. Reflections on methodology

The study has combined a comprehensive literature review, the development of a conceptual framework and two case studies to test this framework. The process was challenging, owing to the size and complexity of the topic (e.g. the range of factors influencing the energy performance of buildings; the variety of processes involved in building construction), the diversity of disciplinary perspectives on this topic (e.g. project and construction management, law and contracts, organisational studies, economics), and the lack of consistency in concepts and terminology (e.g. the multiple classification schemes for construction innovations). It was necessary to make trade-offs between the depth of investigation of particular issues (e.g. the importance of

contract structure) and the breadth of insight obtained from investigating a range of areas.

The next stage is to test this conceptual framework more extensively. The case studies reported above are largely illustrative and more in-depth cases are currently underway. However, there are several methodological challenges in conducting case studies on low-carbon building projects.

First, the successful implementation of an innovation within a project is difficult to establish with certainty. New buildings are complex systems with multiple embedded sub-systems that interact in complex ways. While documents may state that innovations have been taken up, their performance is difficult to measure and cannot be evaluated until a later stage. Research on case study projects must extend into the operational stage and requires both the cooperation of the client and quantitative data on building performance. But the latter is frequently either unavailable, commercially sensitive or available in raw format that requires technical analysis [88]. Aggregation of energy data is also an issue. Depending on the metering strategy, data can be available at whole building level, or broken down into the various energy uses (e.g. small power, lighting, floor by floor, HVAC). It is only in the latter case, where energy data are combined with qualitative information on building uses and occupant behaviours and attitudes, that meaningful insights can be drawn on performance.

Second, there can be a bias in research design towards positive cases. While protocols are available for measuring energy performance and occupant satisfaction, they may only tell part of the story. It only through in-depth discussions with clients, user-groups and project teams that the combination of factors that explain building performance can be identified. Since these groups have a vested interest, there is a potential bias towards reporting of positive outcomes. This is where triangulation of data is important to ensure validity.

Third, construction projects involve temporary coalition of firms that are dismantled after handover, making qualitative narratives difficult to reconstruct. There is rarely any documentary evidence on the qualitative aspects of project delivery, and unless the project was completed recently it may be difficult to identify and contact the people involved. Also, time pressures and confidentiality concerns can make people reluctant to co-operate, and they may not be able to recollect all the relevant details.

8.2. Implications for research

The research has demonstrated the multiplicity of mechanisms by which collaboration, championing and user-involvement can be embedded into projects. The effectiveness of these mechanisms is in turn influenced by contextual variables, such as the experience of project participants, the characteristics of the project and the nature of the client organisation. This has significant implications for research methods. The average effect of a variable may not be of primary importance: instead, attention should be focused on how a causal mechanism (or mechanisms) might have greater impacts when combined with particular contextual conditions. This can be investigated through comparative research designs, and particularly through the use of Qualitative Comparative Analysis (QCA) with 'intermediate *N*' samples [89]. This approach is particularly valuable where theory building is necessary [90].

There is also a need for interdisciplinary studies of the relationship between integration, innovation and building performance. These would study construction as an inter-organisational and inter-personal setting, where different systems (e.g. financial, logistics, design, building, procurement, demand and supply etc.) need to be coordinated to achieve common goals. These relationships can be explored through ethnographic research and longitudinal case studies at project, firm and industry levels. Qualitative research could also explore the impact of relational and behavioural factors on the delivery of low-carbon buildings. Mixed methods offer the potential to combine surveys of a large number of low-carbon projects with in-depth case studies of individual projects to both test and explain the relationships between integration, energy performance and low-carbon innovation.

8.3. Implications for industry and policy

For industry, the framework highlights the need for three types of SCI, namely: a) between the AEC industry and upstream actors such as manufacturing; b) internally within AEC supply chains; and c) with downstream actors such as users and managing agents. The choice of procurement and communication methods, together with the compatibility of project participants, can have a strong influence on project outcomes. The use of collaborative tools established through partnering arrangements, long-term relationships between supply chain actors and the early involvement of sub-contractors and suppliers can all facilitate greater collaboration and greater take-up of low-carbon innovations. Strategic partnering between supply chain actors can encourage long-term relationships and create feedback loops between clients, supply chain actors and users. Since collaborative relationships evolve more effectively when not constrained by formal contracts, integration strategies based on shared values and codes of conduct rather than formal contractual clauses can promote trust and mutual respect and facilitate collaborative exchanges [91,92].

Given the diversity of clients in construction and the building-enhancing character of low-carbon innovations, there is a need for champions of low-carbon innovations, both within individual projects and in the overall supply chain. In projects, the role of low-carbon champions needs to be strengthened by ensuring they have both the agency and the capacity to promote and foster change. To this effect, the role of the system integrator should span both design and construction and involve both the establishment of supply chain networks and their management and coordination [70]. One of the primary roles of a systems integrator is to ensure that all supply chain actors have understand client processes and can align their own systems to those of the client [65]. Beyond projects, innovation brokers and champions can bridge demand and supply and enable co-ordination between actors in the innovation process [80].

Due to the diversity, complexity and fragmentation of this sector, a portfolio of policy instruments is required to encourage emissions reductions [7]. Policy packages need to: (i) encourage greater collaboration in AEC through public procurement practices based on relational norms rather than complex, adversarial contracts; (ii) promote and safeguard low-carbon knowledge networks and cross-firm and cross-sector partnerships that link clients, supply chains and users; and (iii) improve 'energy literacy' within all construction occupations by providing training on low-carbon technologies, processes and management practices [93]. Several initiatives are underway, including the UK government's commitment to halve energy use from buildings by 2030, the Transforming Construction programme, trials of new procurement models (as reported in the UK Government Construction Strategy 2016–2020), and stakeholder initiatives such as the Better Buildings Partnership that aim to improve the sustainability of commercial buildings. But much more needs to be done to bring those initiatives together and to accelerate the transition towards a low-carbon built environment.

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Appendix A

No		Change in linkages (a)	Degree of change (b)	User dependency level	Corresponding Domain	References	Rationale/Narrative
1	Biomass Boiler	6	7	2	C	[94]	Technology replaces conventional boilers. Architectural, mechanical and public health disciplines involved. May also require groundworks sub-contractors during construction stage. Low-levels of user dependency, as it operates as conventional boiler with the exception of fuel storage and maintenance requirements that differ from conventional boiler set ups.
2	Solar thermal water heating	7	3	1	C	[95]	Thermal solar panels are fitted on roofs or walls and feed pre-heated water in hot water cylinder.
3	Air source heat pump	9	10	1	E	https://www.homebuilding.co.uk/a-guide-to-air-source-heat-pumps [96]	Some coordination between mechanical, electrical and public health disciplines is required. Noise is an issue so other disciplines might need to be involved during design stage. Depending on the heating system (e.g. underfloor heating), flooring trades need to be involved.
4	Ground source heat pump	15	13	1	E	[97,98]	Other disciplines involved at feasibility and planning stages (e.g. geothermal, ground investigation and civils). Design of overall system relies on coordination between main disciplines identified and suppliers.
5	Water source heat pump	13	11	1	E	http://thegreenhome.co.uk/heating-renewables/heat-pumps/water-source-heat-pumps-explained/	Water-source heat pumps require a suitable local water source, such as a lake, river, well or borehole. Similar to ground source heat pumps, with ground investigation undertaken at early stages. Sequencing of works is an important element as well as commissioning of components etc.
6	Inter-seasonal heat storage with heat pumps	15	12	1	E	[99,100]	Use of heat pump systems coupled with thermal storage to reduce loads on supply grids. Architectural and structural implications of the design of the thermal store. Similarly, groundworks and flooring trades as well as mechanical and electrical will be required.
7	Combined Heat and Power (CHP)	9	10	1	E	[101,102]	Architectural sizes plant room/energy centre. Combined heat and power (CHP) integrates the production of usable heat and power (electricity), in one single, highly efficient process. Consideration needs to be given at early stage as to the feasibility of CHP on site, with designers calculating heating loads in order to assess feasibility and of size the system. Electrical and mechanical disciplines are involved. Air quality and Nox emissions issues may dictate involvement of environmental specialists. Links between electrical, mechanical and plumping are necessary during construction, as well as links to product suppliers that on some occasions also offer to supply a service-based contract.
8	Combined Heat and Power (CHP) Trigeneration - Gas fired	9	14	2	E	https://www.gov.uk/guidance/combined-heat-and-power [101,102]	Trigeneration is the simultaneous production of electricity, heat and cooling, combining a cogeneration plant with absorption or adsorption refrigeration system. Similar linkages required as with CHP technology.

9	Biomass CHP	9	12	2	E	https://www.gov.uk/guidance/combined-heat-and-power [101,102]	Biomass CHP will consist of similar technologies to gas CHP with the added complexity of storing for fuel and access. Architectural discipline involved on this latter aspect. Links between electrical, mechanical and plumping are necessary as well as links to product suppliers that on some occasions also offer to supply service-based contracts.
10	Combined Heat and Power (CHP) Trigeneration - Biomass	9	14	2	E	https://www.gov.uk/guidance/combined-heat-and-power [101,102]	Combination of technologies 7, 8 and 9.
11	Fuel cell CHP	9	18	5	H	[103] https://www.cibsejournal.com/technical/small-and-mighty-the-performance-of-a-fuel-cell-micro-chp/	Fuel cell technology steers energy conversion away from combustion engines and entails great degree of change. Other than main disciplines involved as above, this technology may involve other disciplines on fire, health and safety issues.
12	Photovoltaics (roof mounted)	5	9	3	F	[104]	Architectural discipline covers several challenges to this technology such as roof availability, roof orientation, shading/ shadowing. Represent substantial change in concept, as renewables with ability to feed back to the grid. Cleaning and maintenance, as well as energy management user involvement.
13	Photovoltaics (integrated)	7	9	3	F	[105]	Similar to 12 but greater linkages required as solutions are now integrated into existing fabric and building systems.
14	Wind turbines (Integrated)	9	10	2	E	[106]	Architectural, electrical and structural considerations. Represents a change in core concepts as it is an on-site renewable source.
15	High performance insulation	8	6	0	E	[107]	This technology covers insulation products that go beyond traditional properties into new materials and new performance specifications that would require changes in design and construction e.g. thinner insulation products, gel-based materials etc.
16	Integrated/Smart Facades	9	11	5	H	[108]	Smart facades are typically supplier-led and require linkages between most disciplines at design and construction stages.
17	Green roofs	9	11	3	H	[109] [130]	Green roofs are a passive measure that improves energy performance through better insulation values and minimisation of heat island effect. Coordination and linkages are required between most (if not all) main disciplines at design stage.
18	High performance glazing	5	7	2	C	[110]	Glazing specification impacts architectural design, artificial lighting strategy and structural feasibility of design options. Artificial lighting control and impact may need involvement of lighting discipline, electrical, engineers.
19	Integrated shading	7	6	1	C	[111]	This technology refers to specification of automatically and building integrated shading solutions. Coordination between architectural and MEP discipline is important. Some structural considerations also relevant at design stage.

20	Solar water air heating – aspirated collection	5	17	5	F	[112]	Solar thermal technology in which the solar energy is captured by an absorbing medium and used to heat air. Mechanical and architectural disciplines involved. Supplier led as it is the fabric material that delivers the process.
21	Solar air heating – Trompe wall	5	8	3	F	[113]	Passive solar building design. Similar to 20 but achieved through architectural design rather than fabric material by creating glazed layer on façade, hence less change in concept.
22	Hybrid lighting system (Fibre Optics)	5	5	2	C	[114]	Method of lighting that combines use of solar light with artificial light to illuminate buildings. Solar light is directed through fibre optic cable bundles and this light is supplemented with some type of artificial lighting.
23	Low energy light bulbs	4	5	2	C	–	Base line technology including LED lighting.
24	Light tubes/Pipes	5	7	2	C	[115]	Structures used for transporting or distributing natural or artificial light for illumination. Architectural and mechanical disciplines involved.
25	Building Energy Management System	6	7	4	F	DETR Good Practice Guide 246	A computer-based energy management and building control system installed in buildings that controls and monitors the building's mechanical and electrical equipment such as ventilation, lighting and power systems.
26	Building Lighting Management System	4	6	3	F	[116]	Lighting automation control system. Architectural and electrical disciplines related to this technology. Operational issues and user overrides sometimes results in adverse outcome of higher energy use or dissatisfaction.
27	Integrated controls (temperature and lighting)	6	8	4	F	[116]	Temperature and lighting controls through sensors based on light levels, occupancy patterns and localised demand. Operational issues and user overrides sometimes results in adverse outcome of higher energy use or dissatisfaction.
28	Artificial Intelligence Controls	6	15	5	C	[117]	Artificial Intelligence (AI) controls optimize energy performance by use of algorithms were developed for the control of the subsystems of an intelligent building. High levels of novelty and low levels of linkages.
29	Waste Heat Recovery	8	9	1	E	[118]	The technology involves utilisation of waste heat from other building processes, such as ventilation etc. Mechanical discipline mainly involved. Requires extensive automatic controls to allow for seasonal and other variations - so that heat is recovered only when needed.
30	Demand controlled mechanical ventilation	3	8	3	F	[119]	Automatic adjustment of ventilation equipment according to occupant choice. DCV is a control method that modulates the volume exchange of fresh or outside air into an enclosed space by mechanical air conditioning equipment. Mechanical and electrical linkages.
31	Hybrid Mixed Mode Ventilation	4	9	3	F	[120]	Combination of natural ventilation from operable windows (either manually or automatically controlled), and mechanical systems that include air distribution equipment and refrigeration equipment for cooling.

32	Natural Cooling (Phase Change)	7	8	2	C	[121]	Coordination between mainly mainly mechanical, electrical and architectural is needed at early stages. Heating option is also available from some manufacturers. Fire safety and IAQ must be considered.
33	Chilled beams	6	7	2	C	[122]	This is a technology that works on convection. Pipes of water are passed through a 'beam', which is integrated into the ceiling or suspended from the ceiling. Architectural discipline is highlighted as relevant because layout of ceiling beams will have impact on space design and layouts, and sometime this systems causes issues with architects. Electrical discipline links needed for controls.
34	Thermal labyrinth cooling	10	8	2	E	[123]	A thermal labyrinth decouples thermal mass from the occupied space, usually by creating a high thermal mass concrete undercroft with a large surface area. Requires coordination and linkages between disciplines at early stage, as it involves building fabric and MEP services design elements. Other consultants also would need to get involved, on health and wellbeing aspects and feasibility.
35	Passive Stack Ventilation	5	7	2	C	[124]	Passive stack ventilation (PSV) is an alternative to mechanical ventilation. Architectural and mechanical disciplines involved. May impact building design.
36	Wind catchers	6	7	2	C	[125]	Wind towers or wind catchers are small towers installed on top of buildings allowing for thermal comfort during summer months. Some coordination between architectural, mechanical and electrical disciplines (controls) is required during design stage.
37	Displacement ventilation	7	8	3	F	[126,127]	Displacement ventilation (DV) It is a room air distribution strategy where conditioned outdoor air is supplied at a low velocity from air supply diffusers located near floor level and extracted above the occupied zone, usually at ceiling height. Affects space design so architectural and MEP linkages required.
38	Radiant heating and cooling	7	8	3	F	[128]	The system involves temperature-controlled surfaces that exchange heat with their surrounding environment through convection and radiation.
39	Earth Tubes	9	9	2	E	[129]	An earth tube is a long, underground metal or plastic pipe through which air is drawn. Architectural and mechanical disciplines as well as other disciplines as cleaning and growth of mould, and indoor air quality impact must be considered.
40	Passivhaus	12	15	5	H	http://www.passivhaus.org.uk/	An overall building servicing certification system based on air-tight construction with mechanical ventilation and high insulation levels. Highly systemic process with most disciplines affected and core concepts impacted.

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